Segmentation of Twisted Super Clean Wire in Creep Experiment[1]

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Abstract

The static torsion creep experiment with the OTEVA® 70 SC Super Clean steel wire reveals for some temperatures a peculiar behavior. In the creep experiment the applied torque moment was constant and the twist angle was acquired. Several experiments were performed for different constant torque and constant temperatures. For most single experiments the twist angle was a gradually increasing function of time. After the elastic unloading the surface of the wire in these cases was textured due to plastic deformation and demonstrates helical, screw-formed spirals with the constant slope over the length of the wire.

However, for certain moments and elevated temperatures the abnormal behavior was observed. In the anomalous cases the wire demonstrated the sectional plastic behavior. The observed twist angle due plastic deformation along the wire was different along the wire length. The dependence of angles along the wire length demonstrates distinct segmented structure. In some segments the residual plastic deformation is considerably higher, as in other segments. The surface of the unloaded wire in these cases was textured differently and demonstrates broken screw-formed spirals with two distinct slopes over the length of the wire. During the active loading phase the jumps in the twist angle of the wire as the function of time were recorded. The number of jumps corresponds to the number of texture segments on the surface of the wire.

1 Experimental observation

In the static torsion creep experiment the OTEVA® 70 SC is a Super Clean steel wire [1] was tested. The material projected for the manufacture of valve springs that require high fatigue properties and relaxation properties at moderately increased operational temperature.

The constant moment torsion unit is used for the creep test. The constant moment torsion unit has one fixed end that is holding the metal rod with a grub screw and does not rotate. The other end is fixed with a grubbing also but is free spinning with a pulley. It has string wound onto the pulley in the opposite direction that the torque is going to be applied; it also has a carriage that is to house the weights that will be added with each measurement. The pulley end of the equipment also has a 360 degree readout that is to measure the difference in angle as the different weights that are applied, this readout measures in degree increments. The constant moment torsion unit is enclosed in the constant temperature furnace. Each sample wire was tested under the certain constant moment and constant temperature. The moment acting on the wire was increased in steps. At the experiments under the moderate moment the behavior was typical for a creep. The twist angle was

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[1] Manuscript for 2017 Conference for Spring Technology, University of Ilmenau, Germany, https://www.tu-ilmenau.de/stz-federntechnik/ilmenauer-federntag-2017/

continuously increased in time and the twist rate $d\phi / dx = \theta$ remains nearly constant over the length of the wire, slightly increasing in time due to creep of the wire [2]. However, with the increased moment the abnormal behavior was observed. Under the action of a certain moment the wire demonstrated the sectional plastic behavior. The constant moment was applied. Initially the wire was twisted nearly homogeneous twist rate θ_A. The observation of twist rate is evident due to the structure of longitudinal traces or strips that remain after cold drawing process of wire. After a couple of seconds the first zone B with the higher value of twist rate instantly appeared. In the emerged zone B the twist rate θ_B remains nearly homogeneous. The strict boundary between zone B and zone A is clearly visible and rotationally symmetric. Immediately after the forming of the first zone A the second zone B appeared. The twist rate θ_B in the second zone B was the same as in the first zone. The new zones B appeared again and again, such that full length of wire was covered by a nearly periodic structure of zones B and zones A. After a couple of seconds the process of zone emergency finished and the plastic deformation of wire stopped. After the elastic unload of the wire the zones remained clearly visible on the surface of the wire. The structure of zones is shown on the **Fig.1**. On this figure the microphotographs of the surface of both zones with different magnification are shown. The grooves on the surface of zones B are deeper in comparison with the depth of grooves on the surface of zones A.

The hardness and the microstructure of the wire on the diametric cut was investigated. The hardness was acquired over the rectangular array over each zone. The rows numbers of hardness array correspond to the position over diameter of wire. The rows with number 1 and 6 are near the surface of the wire, 3 and 4 near its axis. The columns are ordered along the wire axis. On the **Fig. 2** the averaged hardness over the rows in both zones is shown. The Vickers hardness is nearly the same in both zones, as shown on the **Fig.2**. The microstructure images over the diametric cut are shown on the **Fig. 3** with different magnification. No significant differences could be reported.

2 Explanation as a material instability

A possible explanation of the observed phenomenon is the slight variation of the material properties along the wire axes. The shear-stress-shear-strain curves differ along the wire length.

For a qualitative description the following expression of the shear-stress-shear-strain curve is assumed:

(1) $\tau(\gamma) = \left(G - 3c\gamma_0^2\right)\gamma + c\left((\gamma - \gamma_0)^3 + \gamma_0^3\right).$

The value γ_0 depicts the position of the saddle point of the stress-strain curve. The parameter c is the nonlinearity modulus. For $c = 0$ the stress-strain curve is linear. For $0 \leq c < c_0$, where

(2) $c_0 = G/(3\gamma_0^2)$

the stress-strain curve is monotonically increasing function. If $c_0 < c$, the curve possesses a region with a negative slope. The initial tangent shear modulus of the material independently upon parameter c is G. The family of stress-strain curve with different values of the parameter c is schematically depicted on the **Fig.4.** With the assumed shear-stress-shear-strain curve the analytical expression for torque is possible. Using the expression (1) the torsion moment

(3) $M = 2\pi \int_0^R \tau r^2 dr$

reads as

(4) $M = \pi\theta R^4\left(10c\theta^2 R^2 - 36c\gamma_0\theta R + 15G\right)/30.$

The first and second derivatives of the torque with respect to twist rate are respectively

(5) $dM/d\theta = \pi R^4\left(10c\theta^2 R^2 - 24c\gamma_0\theta R + 5G\right)/10$, $d^2M/d\theta^2 = 2\pi R^5 c\left(5\theta R - 6\gamma_0\right)/5$.

The saddle point of the torque is at

(6) $\theta_1 = 6\gamma_0(5R)^{-1}$.

At the saddle point the slope of the torque curve is

(7) $dM/d\theta\big|_{\theta=\theta_1} = \pi R^4\left(-72c\gamma_0{}^2 + 25G\right)/50$.

The slope is positive, if

(8) $c < c_1 = 25G/(72\gamma_0^2) \equiv 25c_0/24$.

In this case, the twist angle increases monotonically with the increasing torque. These behaviors illustrate the black and green curves on the **Fig.5**. During the elastic unload the equilibrium position with the twist rate θ_A is attained. The unloading from any attained point of the curve occurs elastically and follows the straight green line A. In this case the twist angle was a gradually increasing function of time, as shown by the graph A on **Fig.6**. The wire has the diameter 3.7 mm, the constant temperature was 150°C and the torsion moment 10.14 Nm. This moment corresponds to the shear stress on the surface of 1000 MPa.

Generally saying, the torque curve possesses the regions with negative slope, as shown by the blue and red curves on the Fig 3. In this case the behavior of torque, as the function of twist rate, is not smooth. The torque arrive its maximum value and jumps to the second increasing branch of the function. Due to jump, the second equilibrium position θ_B demonstrate considerable higher values of twist rate, then the first residual twist rate θ_A. Apparently, at the stress-strain curves of the material at the temperature of measurements do not differ essentially. A small increase of the moment leads to the agglutination of the zones B into one continuous zone, such that the regions A with minor twist rate disappear. During the active loading phase the jumps in the twist angle of the wire as the function of time were recorded (Line B on the **Fig.6**). The number of jumps corresponds to the number of texture segments on the surface of the wire. The wire has the diameter 3.7 mm, the temperature was 150°C and the torsion moment 13.92 Nm. The applied torque corresponds to the shear stress on the surface of 1372 MPa.

The another possible explanation of the observed behavior could be twinning induced plasticity effect [3,4]. This form of transition to plasticity was observed for austenitic steels with a high manganese content. The twinning-induced plasticity effect is a competitive plasticity transformation to the dislocation gliding **(Fig. 7).**

3 Conclusions

An interesting behavior of wire was observed during the static torsion creep experiment with the OTEVA® 70 SC Super Clean steel wires. For certain moments and elevated temperatures the abnormal behavior was observed. The surface of the unloaded wire demonstrated the sectional plastic behavior of textures. The observed twist angle due plastic deformation along the wire was different along the wire length. A possible explanation of the observed phenomenon is the slight variation of the material properties along the wire axes.

Compliance with Ethical Standards:

The authors declare that they have no conflict of interest.

References

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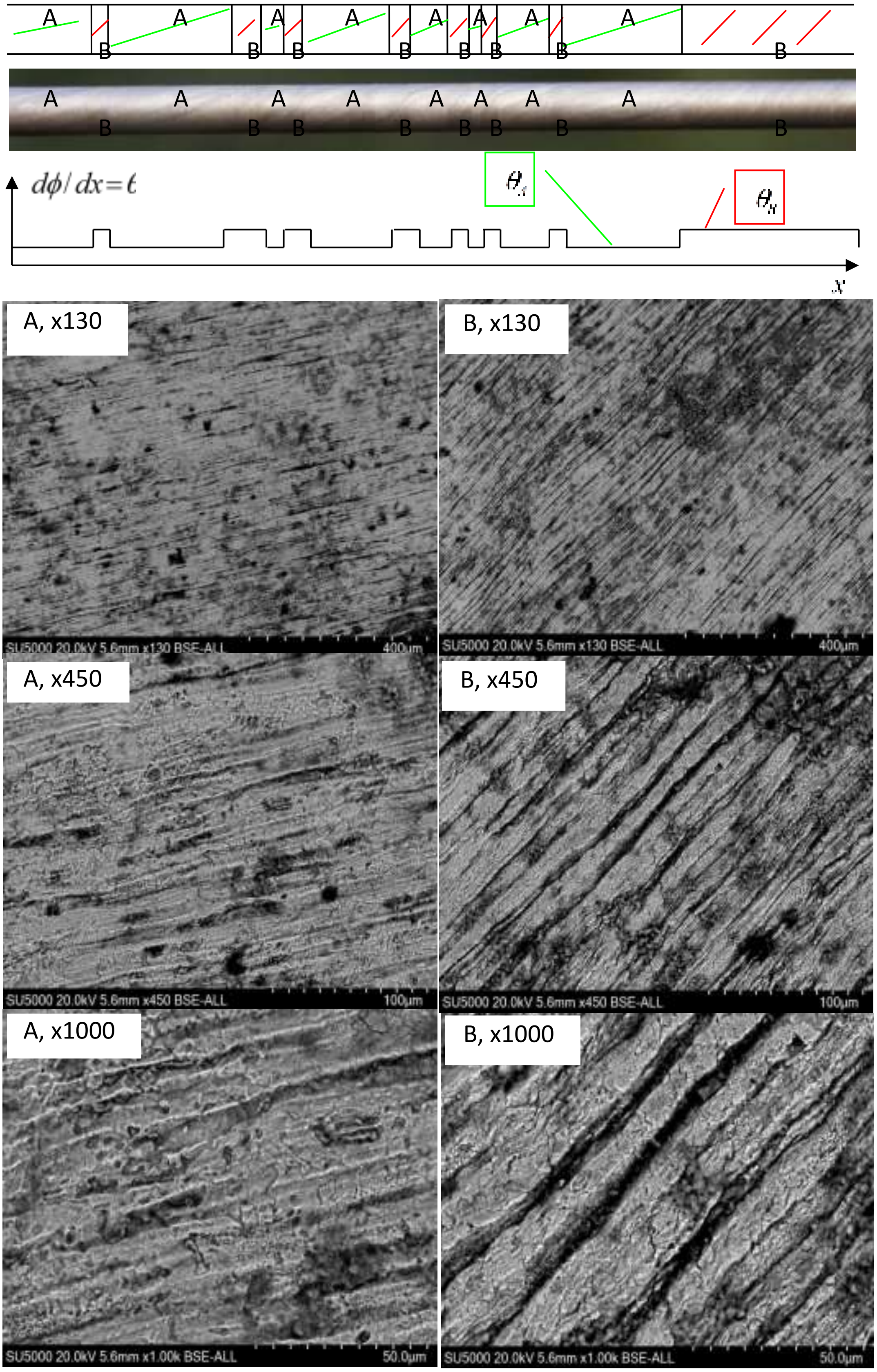

Fig. 1 Microstructures of zones with different plastic twist rates over the outer surface of wire

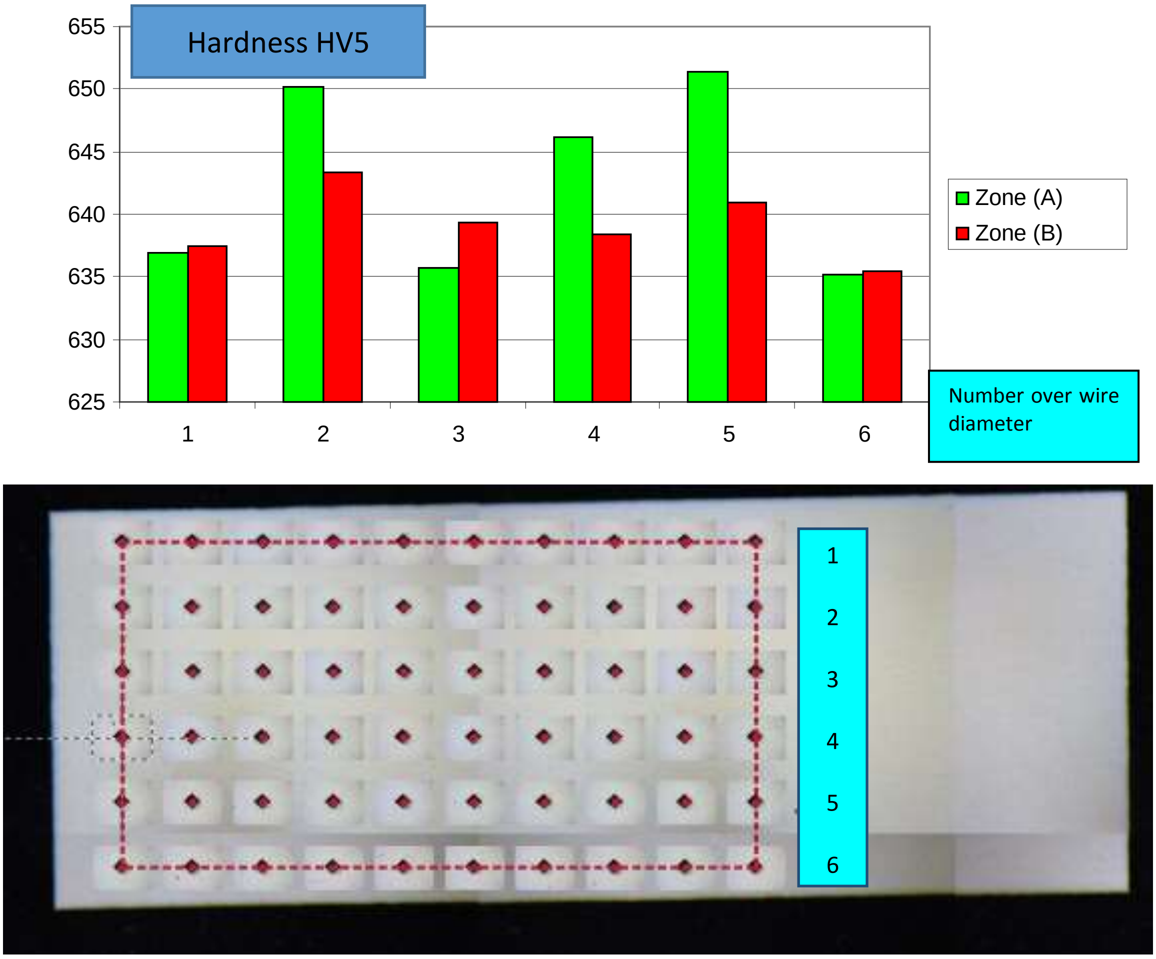

Fig. 2 Results of hardness measurement HV5 over the diametric cut of the wire

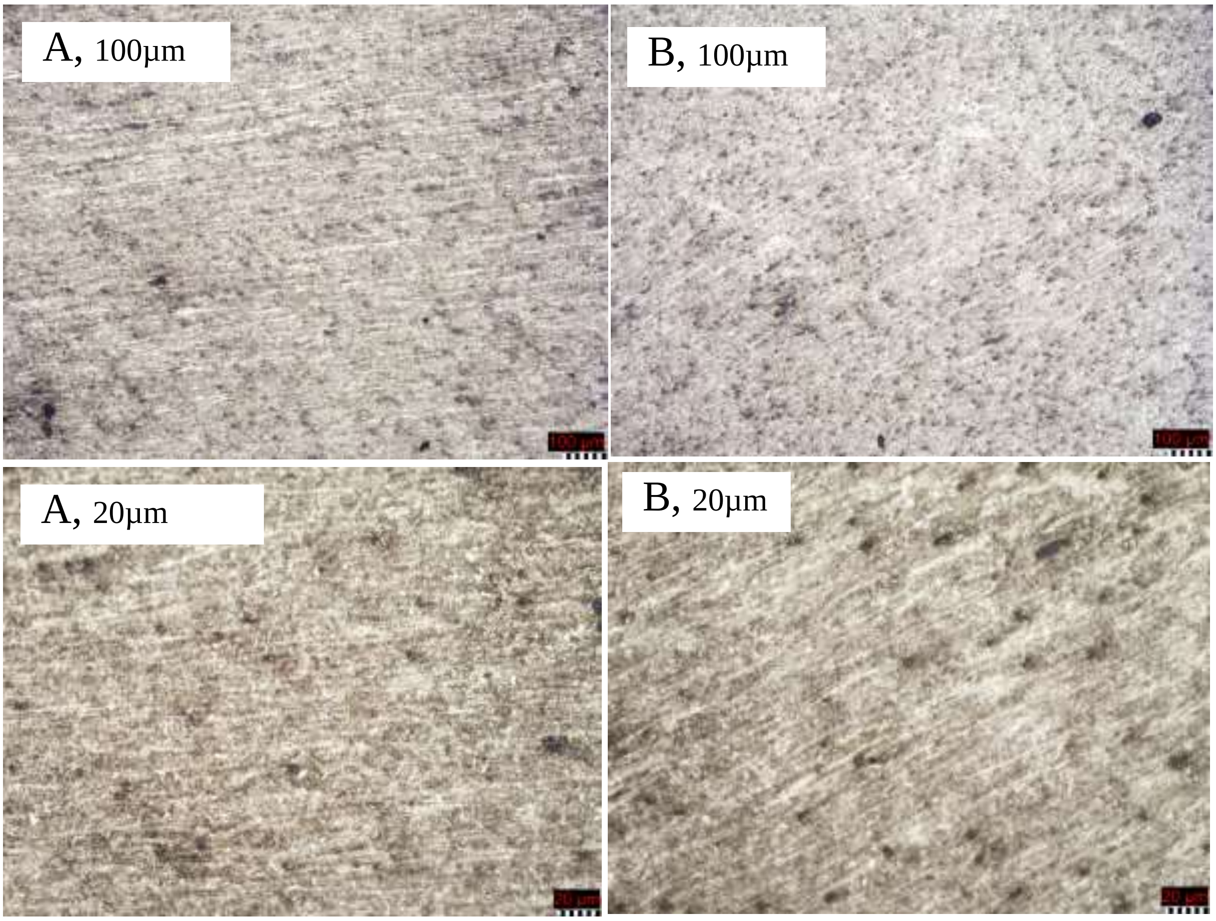

Fig. 3 Microstructures of zones with different plastic twist rates over the diametric cut of the wire

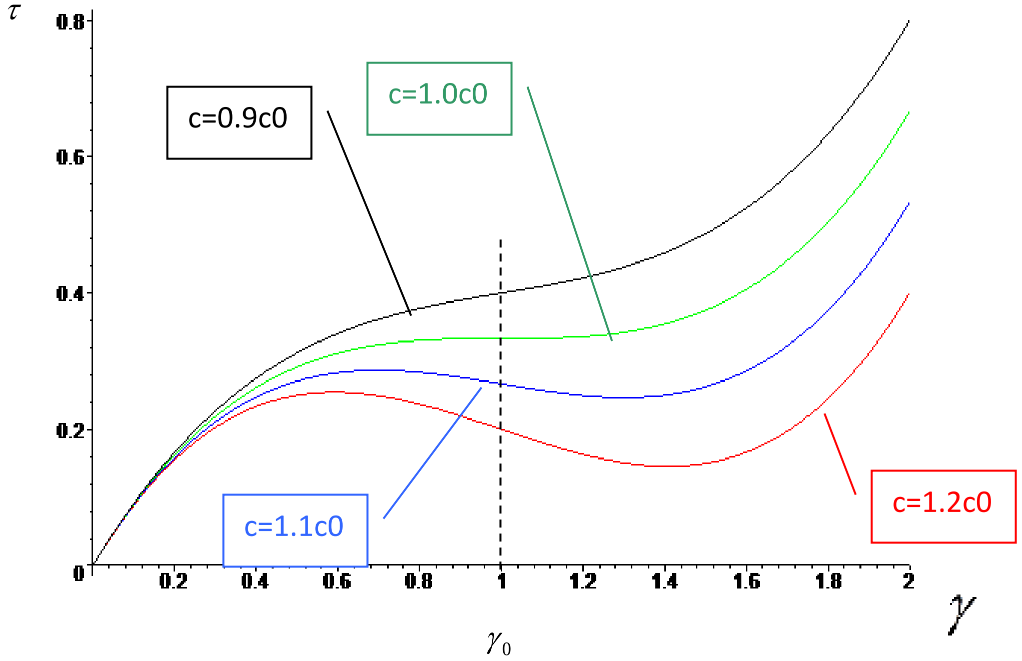

Fig. 4 The nonlinear shear stress- shear curves for different values of parameter c_0

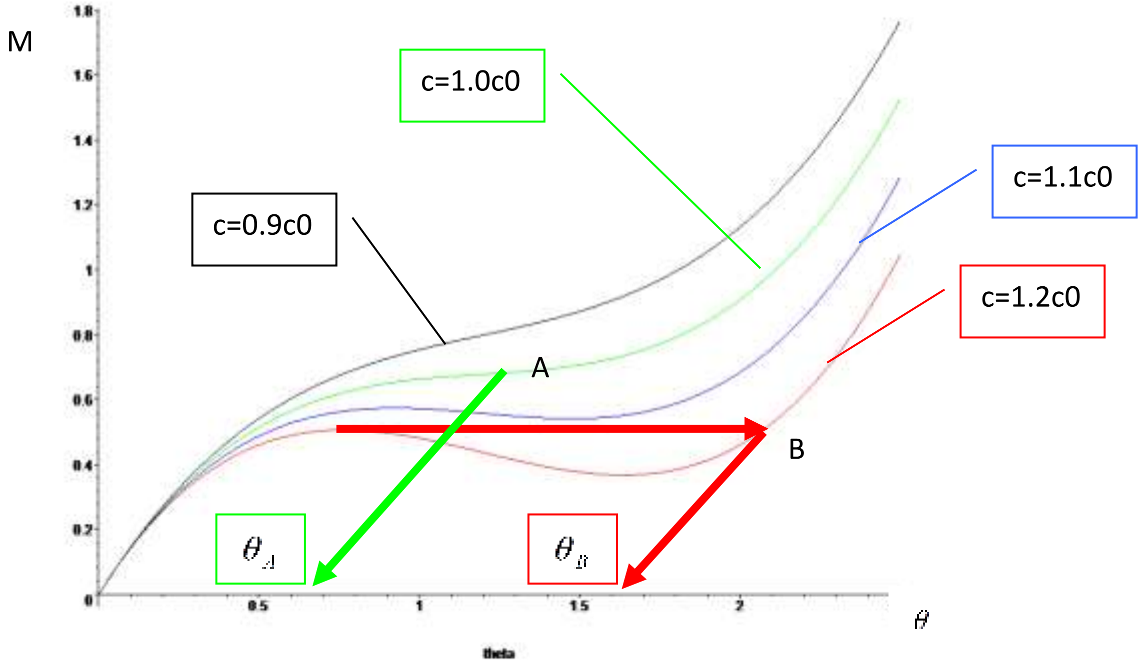

Fig. 5 The torque curves for the different values of parameter c_0

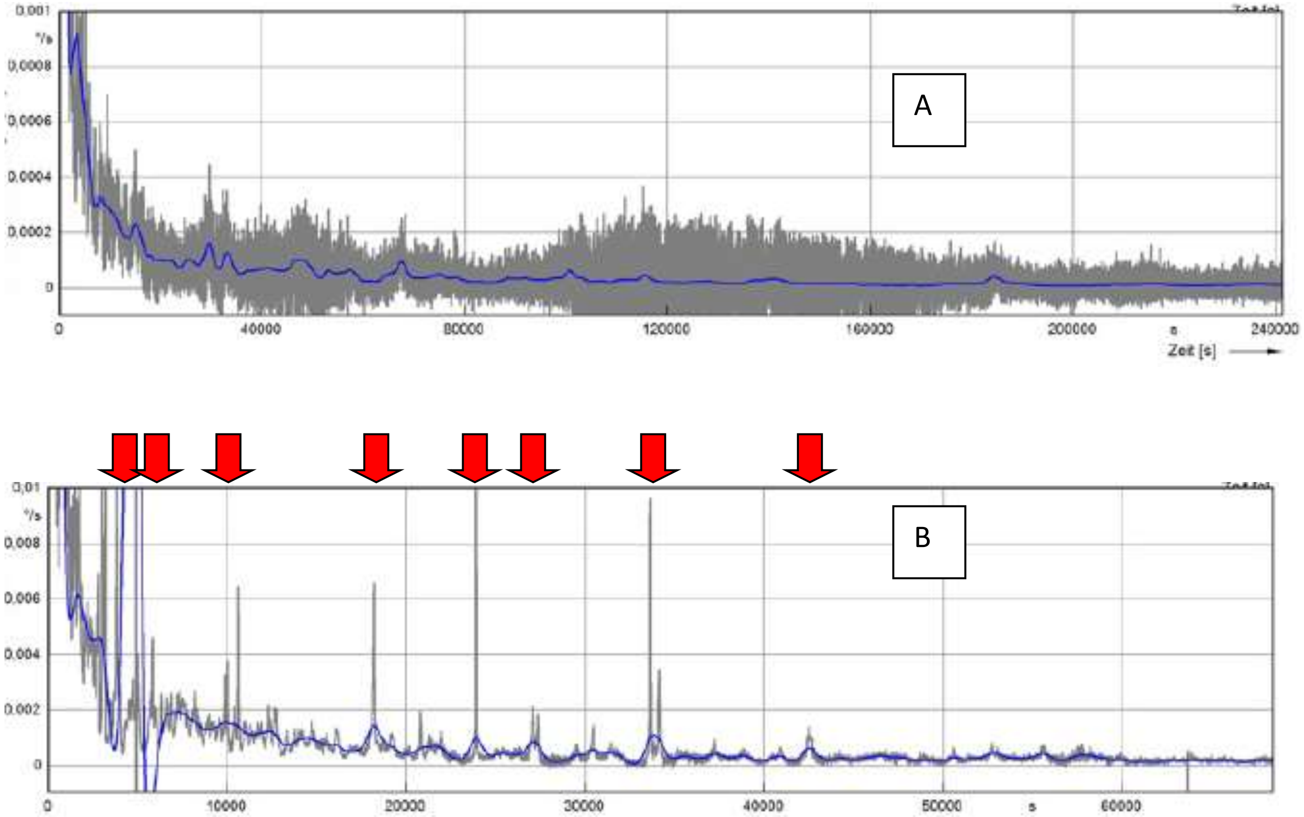

Fig. 6 Continuous decreasing twist rate (A) and twist rate with jumps (B)

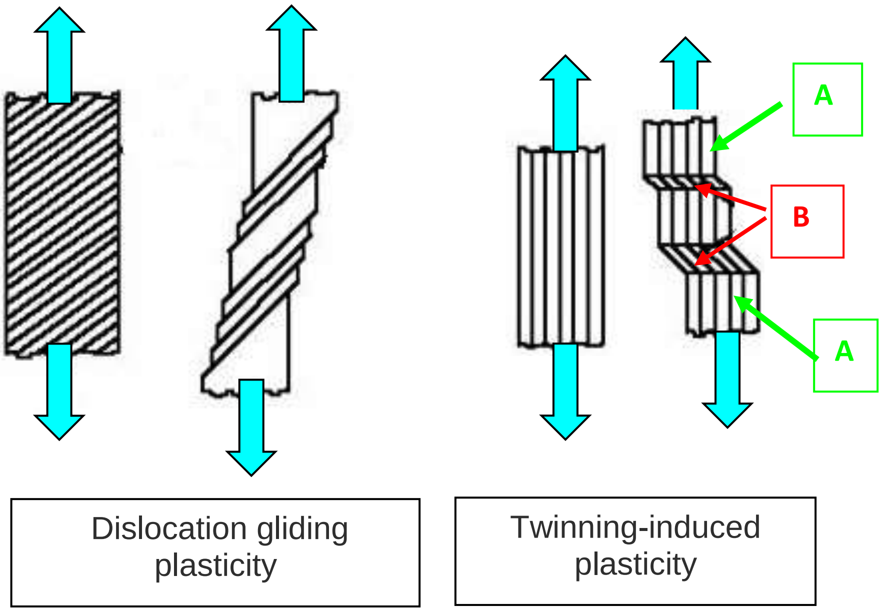

Fig. 7 Alternative mechanisms of plasticity formation